Study of Dry Sliding Wear Behavior of Al-12%Si alloy Produced By Squeeze Casting

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Abstract

The present research deals with study of the effect of applied casting pressure at constant pouring and die preheating temperatures on the microstructure and dry sliding wear behavior of the squeeze cast Al-12%Si alloy was investigated. A pin-on-disc tests were conducted at varying loads from 5 to 20 N and a sliding speed of 2.7m/sec for a constant sliding time of 20min. The results showed that a refinement in the microstructure with increasing the squeeze pressure. The results showed that the wear rates and coefficient of friction (μ) of the squeeze cast samples are lower than that of the gravity die cast sample. The results also showed that the density of the specimens decreased with application of a 7.5 MPa applied pressure, but it increased steadily for higher pressures up to 53 MPa. Increasing the squeeze pressure resulted in increasing the hardness and decreasing the wear rate. These results were explained based on the densification mechanism brought about by the application of pressure during solidification.

Key words: wear resistance, squeeze casting, Al-Si alloy, microstructure, porosity

دراسة سلوك البلى الأنزلاقي الجاف لسبيكة الألمنيوم-12 %سليكون المنتجة بطريقة السباكة بالعصر

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الملخص

يتناول هذا البحث دراسة تاثير ضغط السباكة المسلط عند درجات حرارة صب وتسخين مسبق لقالب الصب ثابتة على التركيب المجهري وسلوك البلى الأنزلاثي الجاف لسبيكة الالمنيوم –12% سليكون المنتجة بطريقة السباكة بالعصر. وأجريت أختبارات البلى من نوع المسمار على القرص عند أحمال متغيرة من 5 -20 نيوتن وسرعة أنزلاق 2.7 متر/ثانية ولفترة زمنية ثابتة 20.دقيقة. واظهرت النتائج حصول تنعيم في البنية المجهرية مع زيادة ضغط السباكة. اظهرت النتائج أن معدلات البلى ومعامل الأحتكاك (μ) للنماذج المنتجة بطريقة السباكة بالعصرأقل مما هو عليه في حالة النموذج المنتج بطريقة السباكة بالجاذبية. واظهرت النتائج ايضا بان كثافة العينات قد قلت عند تطبيق ضغط مسلط مقداره (7.5MPa)، لكنها قد زادت بصورة ثابتة عند تسليط ضغوط اعلى الى حد (53MPa). ان زيادة ضغط السباكة ادت الى زيادة الصلادة وتقليل معدل البلى. ان هذه النتائج قد تم تفسيرها بالاعتماد على الية زيادة الكثافة الناتجة بواسطة تطبيق الضغط اثناء التجمد.

1-Introduction:

Squeeze casting process involves working or compressing the liquid metal in a hydraulic press during solidification which effectively compensates for the natural contraction that occurs as the liquid changes to solid [1]. Squeeze casting has been used for half a century in Russia and is now being exploited in the West. For example ,the Toyota Motor Company in Japan introduced squeeze cast aluminum alloys wheels into their product line for passenger cars in 1979[1]. The aluminum alloy 357 (Al-7Si-0.5Mg) was prepared by sand, gravity die and squeeze casting, the properties of the alloy shows to be clearly superior. The improvement in ductility particularly notable [2,3] .The commercial development of squeeze casting began to take place in Europ, North America and Japan only after 1960 as reported by **Reiss and kron** [4] .

Two types of squeeze casting technology have evolved based on different approaches to metal movement during die filling. These have been given the names direct and indirect squeeze casting [5]. Squeeze casting permanent mold is frequently used to produce safely critical aluminum suspension components. Squeeze cast aluminum components have replaced iron/steel control arms and front knuckles in volume during the last four years. In late 1994, **Delphi Chassis System and Casting Technology Company** [6] began a joint development program for an aluminum front knuckle conversion slated for application on mainstream passenger cast. Squeeze casting was selected based on the superior physical and mechanical properties, dimensional capabilities and integrated process controls.

Davidson C.J et al [2004][7] studied fatigue properties for squeeze, semisolid and gravity die casting, fatigue cracks initiated from oxide defects in the squeeze cast castings and from both oxide defects and shrinkage pores in semisolid and gravity castings. Despite differences in the microstructures and in the defect populations in the squeeze and semisolid casting, their fatigue properties were similar.

Squeeze casting, also known as liquid metal forging, is a combination of casting and forging process as shown in **Fig. 1[8]**. The molten metal is poured into the bottom half of the pre-heated die. As the metal starts solidifying, the upper half closes the die and applies pressure during the solidification process. The amount of pressure thus applied is significantly less than used in forging, and parts of great detail can be produced. Coring can be used with this process to form holes and recesses. The porosity is low and the mechanical properties are improved [2007] [9]. **Fig.2** shows direct squeeze die casting process [10].

The aim of the present work is to study the effect of casting pressure or applied pressure at constant pouring temperature and preheating temperature on microstructure and mechanical properties (hardness)

The sliding wear resistant characteristics of squeeze cast samples were evaluated and compared with these of gravity die casting

2- Experimental Work

2-1 The Used Material

The Al-Si alloy (AlSi12)was selected for its very good castability and excellent weldability, which are due to its eutectic composition and low melting point of 570ºC. The alloy is particularly suitable for intricate, thin walled ,leak-proof fatigue resistant casting and good corrosion resistance [11].

2-2 Gravity Die Casting

The Al-12%Si alloy was melted and poured in die or metallic mold by gravity. For each experiment about 200gm of prealloyed (Al-12%Si) in graphite crucible in an electric resistance Furnace at temperature 700ºC. The melt was poured into a metallic mold which dried before casting operation at 200ºC by using drier type (Heracus). The casting was left to cool down in the air. The specimens of prepared alloy had dimensions of 43.5mm diameter and 25mm height. **Table 1** shows the chemical composition of the 1725 (Al-Si) alloy.

Table 1 The chemical composition of the 1725 (Al-Si) alloy.

Element wt%	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
	12.2	1.2	0.81	0.18	0.08	0.34	0.17	Remainder

2-3 Squeeze Casting System

2-3-1 Hydraulic Press

A vertical hydraulic press (German made) is used (with a ram 70 mm in diameter) to apply the pressure in a perpendicular direction to the squeeze casting die. The press can apply a hydraulic pressure of (1-70) Kg/cm^2, with a constant ram speed of 25 cm/min.

2-3-2 Squeeze Punch

The selected squeeze punch was made of low alloy steel, and designed with a hole in its upper part to be fixed to the ram with two steel bolts. The lower part of the punch is cylindrical in shape with dimensions of 25mm height and 41.5mm diameter. This lower part is used to squeeze the molten alloy.

2-3-3 Squeeze Die

The die is cylindrical in shape with dimensions of 26mm height and 43.5mm internal diameter. The die was made of low alloy steel and consists of two parts joined by two high temperature resistant steel bolts. This design allows the final squeezed composite casting to be removed from the die easily. **Table 2** illustrates the chemical composition of the punch and dies which was done with the portable metals analyzer type 1650 from the ARUN Technology, Germany, available at the Department of Materials Engineering of the University of Technology.

Table 2 The chemical composition of the punch and die steel.

Element	Weight Percent (٪)	Element	Weight Percent (٪)
Fe	93.9	Co	0.02
C	1.0	Cu	0.585
Cr	2.84	Mo	0.0599
Ni	0.936	Nb	0.01
Si	0.227	Ti	0.02
Mn	0.383	V	0.02
Al	0.0253	Sn	0.04

2-4 Tests and Measurements

2-4-1 Hardness and Microstructure Test

A small specimen of alloy (Al-12%Si)(alloy A) and squeeze cast samples (A1,A2,A3,& A4) were prepared by turning processes in the dimensions of 12mm length and 10mm diameter. Wet grinding operation with water was done by using emery paper of SiC with the different grits (220, 320, 500, and 1000). Polishing process was done to the specimens by using diamond paste of size (1µm) with special polishing cloth and lubricant. They were cleaned with water and alcohol and dried with hot air. Etching process was done to the specimens by using etching solution which is composed of (99% H_2O+1%HF), then the specimens were washed with water and alcohol and dried. Vickers hardness test was made by using Vickers hardness tester type (Einsingenbei U/M, Mode Z323)..Diamond indenter was forced into surface of the specimen being tested under a static load of (300 gm) for(10-15)sec. Measurements of the indentation diameter were made in (3-5) readings and the average hardness (VHN) was found.

2-4-2 Density and Porosity Measurements

The density of squeeze cast samples were measured by weighting the sample in air with using sensitive balance type (Denver –max 210 gm) with an accuracy 0.1mg. The volume of cylindrical sample of 20mm length and 10mm diameter was calculated. The actual density (**ρ_{ac}**) can be found from the equation as follows:

$$\rho ac = \frac{weight}{volume} \quad \ldots\ldots\ldots\ldots\ldots..(1)$$

The porosity percentage (**P%**) was measured for the squeeze cast samples by using both the actual density(**ρ_{ac}**) and theoretical density of reference (**ρ_{th}**) ,using equation as follows [12]:

$$P\% = 1 - \frac{\rho ac}{\rho th} \quad \ldots\ldots\ldots\ldots\ldots(2)$$

2-4-3 Wear Tests

Wear specimens were machined from ingot and cut according to ASTM specification D2625-83 of 20mm length and 10mm diameter[13].Then one surface of each specimen was ground and polished to obtain clean and smooth surface.

2-4-3-1 Wear Apparatus

A Pin-On-Disc wear apparatus was used, which was designed according to ASTM specification F732-82[13]. The wear apparatus consists of motor with constant revolution speed (510 rpm).

2-4-3-2 Wear Rate Measurement

Weight method was used to determine the wear rate of specimens. The specimens were weighted before and after the wear test by sensitive balance type (DENVER instrument)(Max-210gm) with accuracy 0.0001 gm. The weight loss (ΔW) was divided by the sliding distance and the wear rate was obtained by using equation as follows [14]:-

$$\text{Wear rate} = \Delta w/S_D \ldots\ldots\ldots\ldots\ldots,(3)$$

$$\Delta w = w_2 - w_1 \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$S_D = S_S * t \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Wear rate (W.R) = $\Delta W / \pi D.N.t$……….(6)
where:
S_D = linear sliding speed (m/sec.)
D = sliding circle diameter (cm)
t = sliding time (min)
N = steel disc speed (rpm)
Hardness of steel disc =35 HRc
Diameter of specimen =10mm
Length of specimen = 20mm

2-4-4 Measurement of Friction Coefficient

The coefficient of friction (μ) was found by dividing the friction force (F) to applied normal load (W) according to the following equation :

$$\mu = F / W \quad \text{…………………(7)}$$

Frictional force is found by a specially designed steel ring taken from calibration apparatus of TQ strain meter mounted on U angle block was fixed on the bench and aligned with the left side of the lever arm. The force was transmitted from the left side of the fulcrum lever to the ring by a 5mm diameter and of 3cm long sliding rod. Two half bridges were formed on inside and outside ring surfaces by means of four strain gauges with gage factor of 2.065 .These strain gages were then connected to TQ-S6072 digital bridge strain meter. Before running the experiment, the digital strain micrometer display cathode ray screen was calibrated to record the micro strain reading before and after running. The reading from the strain meter was taken and the calibration curve of load (force) verses strain was plotted at constant sliding time (20 min),sliding speed (2.7 m/sec) and steel disc hardness of 35HRc.

3- Results and Discussion

3-1 Microstructure and Hardness Results

Vickers hardness results are given in **Table 3.** It is seen that the squeeze cast samples have higher hardness values than that of gravity die cast sample. This is due to rapid solidification and high cooling rate of molten metal under applied pressure which gives smaller grain size and refiner eutectic phase (Al-Si) than that of gravity die cast .The **Fig.3** shows the microsturcture of gravity cast sample (A) which consists of primary phase (α-Al) which represents the matrix of the microsturcture and black color of silicon phase(As flakes). A part of silicon phase is shown as massive silicon (Grey color) in some regions of matrix microstructure. As applied pressure increases the refinement of eutectic phase increases and in comparison with squeeze cast technique , the α-dendrites were much bigger and dentritic structure form as shown in **Figs. 4 ,5 ,6 and 7** for squeeze cast samples (A1, A2, A3 and A4) respectively. The hardness values increases from 83 HV to 121 HV at pressures 7.5 MPa to 53 MPa respectively. It was thought the microstructural changes played important role in increase the hardness value of the squeeze cast.

3-2 Density and Porosity Measurements Results

Casting solidification brings to the shrinkage in the liquid state, solidification shrinkage and shrinkage in the solid state. Recently, technologies of die and gravity casting have increased the number of highly functional castings, which have been characterized with the very complex geometry. Impossibility of adequate feeding results in occurring of stand-alone solidification areas. These areas have been characterized with the smallest cooling and solidification rate and with the volume defects such as shrinkage, micro- and macro porosity appearance **[**15].

The effect of squeeze pressure on density and porosity are illustrated in **Table3**.

Sample Symbol	**P_a MPa**	**Tp °C**	**T_D °C**	**ρ_{ac} g/cm^3**	**ρ_{th} g/cm^3**	**P%**	**VHN Kg/mm^2**
A	**Gravity Die Casting**	**700**	**200**		**2.68**		**70**
A1	**7.5**	**700**	**200**	**2.675**	**2.68**	**0.2**	**83**
A2	**23**	**700**	**200**	**2.59**	**2.68**	**3.4**	**96**
A3	**38**	**700**	**200**	**2.619**	**2.68**	**2.27**	**110**
A4	**53**	**700**	**200**	**2.674**	**2.68**	**0.22**	**121**

Although the density is expected to increase continuously with increasing the applied pressure of squeeze casting, it shows a drop at the minimum used pressure of 7.5 MPa. This is attributed to the existence and segregation of porosities at the center of sample. The main part of shrinkage for the samples solidified under atmospheric pressure has been accommodated by formation of a large shrinkage pipe on the top surface of cast. Upon the application of squeeze pressure, such shrinkage pipe and cavities are pushed down toward the bulk of the samples. Consequently, if the applied pressure is not large enough to eliminate such cavities, smaller density values may be attained. With further increase in the applied pressure up to 53 MPa, gas and shrinkage porosities decrease and hence density increases. These results are in agreement with those of other researchers [15, 16].

Table 3 The actual density, theoretical density, VHN and P%, determination for squeeze casting samples under different applied pressures

ρ_{ac} : Actual density, g/cm^3
ρ_{th} : Theoretical density, g/cm^3
P% : Porosity percentage
VHN: Vickers Hardness Number

Tp : Pouring temperature ,ºC
T_D : Die (Mold) temperature ,ºC
Pa : Applied casting pressure ,MPa

3-3 Wear Test Results

3-3-1 Effect of Applied Load on the Wear Rate and Friction Coefficient(μ)

Fig.8 shows the variation of mass wear rate with applied normal load during wear test for different samples (A, A1, A2, A3 and A4) under dry sliding conditions at a load of 20N, sliding time of 20min and sliding speed of 2.7m/sec. It was shown that the wear behavior of base alloy(Al-12%Si) (sample A) is mild wear (oxidative wear) at low loads (5-10)N, and when the load increases the wear rate increases and transforms to metallic wear at high loads (10-20)N. These results are in agreement with those of other researchers [17,18]. The wear rate of the gravity die cast sample (sample A) is more than that of the squeeze cast samples (A1, A2, A3 and A4) at higher loads (15-20N).

Fig.8 shows also the effect of applied casting pressure on the wear rate of different samples (A1, A2, A3,and A4) under dry sliding conditions at a load of 20N, sliding time of 20min and sliding speed of 2.7m/sec. The sliding wear rate reduces or wear resistance increases with increasing the applied casting pressure which was used to press the molten alloy in the die cavity during squeeze casting of alloy Al-12%Si). This is due to increase in the hardness value as the applied pressure increases because of the reduction of shrinkage porosity as a result of bulk deformation and improving of filtration feeding action during solidification under pressure in squeeze casting [19].

Prasad B.K.[2006][20] studied sliding wear of a grey cast iron (similar in microstructure by presence of silicon flakes in aluminum phase) under varying test environments and speed and pressure conditions. He concluded that the wear rate of cast iron increases with speed and pressure of sliding due to increasing severity of wear condition. The specimens tended to lose proper contact with the disc at larger pressure (load) when slide dry [21].

The effect of the sliding time on friction coefficient (μ) is shown in **Fig.9.** It is clear that the friction coefficient of all samples increases with increasing sliding time, this increase being more pronounced at the beginning of the wear test, then the (μ) tends to be in steady state after about 10 minutes of wear test. This observation is due to the gradual flattening of asperities with the sliding time and increasing the real contact area. This was mentioned by some other researchers [22, 23].

3-3-2 Effect of Sliding Time on the Wear Rate

Fig.10 shows the variation of wear rate with sliding time for different samples (A, A1, A2, A3 and A4) under dry sliding conditions at a load of 20N and sliding speed of 2.7m/sec. It can be seen that as the sliding time increases, the wear rate for all samples of alloy (Al-12%Si) increases. These results are in agreement with those of other researchers [22, 23]. This is explained in term of action of both oxide layer on the sample surface and formation large wear debris particles which is reflected in larger wear rate at longer sliding time. These effects are more in case of gravity die cast sample. The results in **Fig.10** shows that the wear rate of the gravity die cast sample (sample A) is more than that of the squeeze cast samples (A1,A2,A3 and A4) at all sliding times (10-60)min.

3-3-3 Worn Surface Results

Fig.(11a,b,c,d and e)shows micrographs of the worn surfaces of the gravity die cast sample and squeeze cast samples (A,A1,A2,A3 and A4) respectively at a sliding speed of 2.7m/sec and a load of 20N, and for sliding time of 20min during wear test. The worn or damaged surfaces shows continuous grooves and cracking of long wear track. In some places ,some plastic deformation, together with presences of fine oxides debris particles are also observed in case of gravity die cast sample. While it is seen a smooth and glassy finish and faint wear lines in the direction of sliding on worn surfaces, that indicates a mild abrasion wear mode is present in case of cast samples which squeezed at applied pressure (53 MPa).

4- Conclusions

1- The microstructure examination showed that small grain size and refine eutectic phase morphologies had been obtained in squeeze casting with respect to gravity die casting.

2- The samples were produced by squeeze casting technique had higher Vickers hardness values and wear resistance than that of the gravity die technique.
3- As the applied casting pressure for squeeze cast samples increases the hardness value and wear resistance increases.
4- The actual density of squeeze cast samples was improved and approached the theoretical density because of the reduction of shrinkage porosity as applied pressure increases during solidification in squeeze casting.
5- With increasing the sliding time the coefficient of friction increases until a steady state is reached.
6- Wear rate increases with increasing applied normal loads and sliding times at constant sliding speed for all investigated samples.
7- Faint wear lines in the direction of sliding on worn surfaces indicates that a mild abrasion wear mode is present for squeeze cast sample which produces at higher applied pressure(53 MPa).

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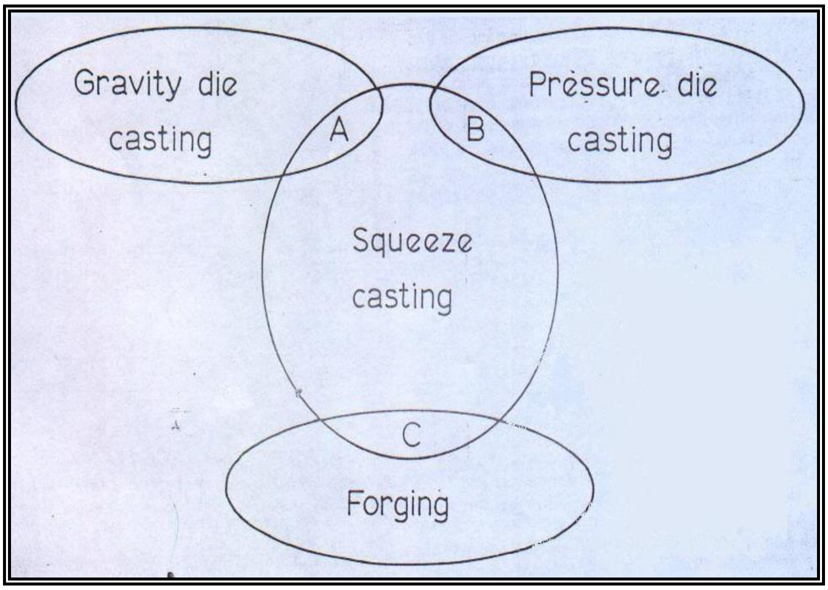

Fig. 1 Squeeze die casting process as a combined process of gravity die casting, pressure die casting and forging processes [8]

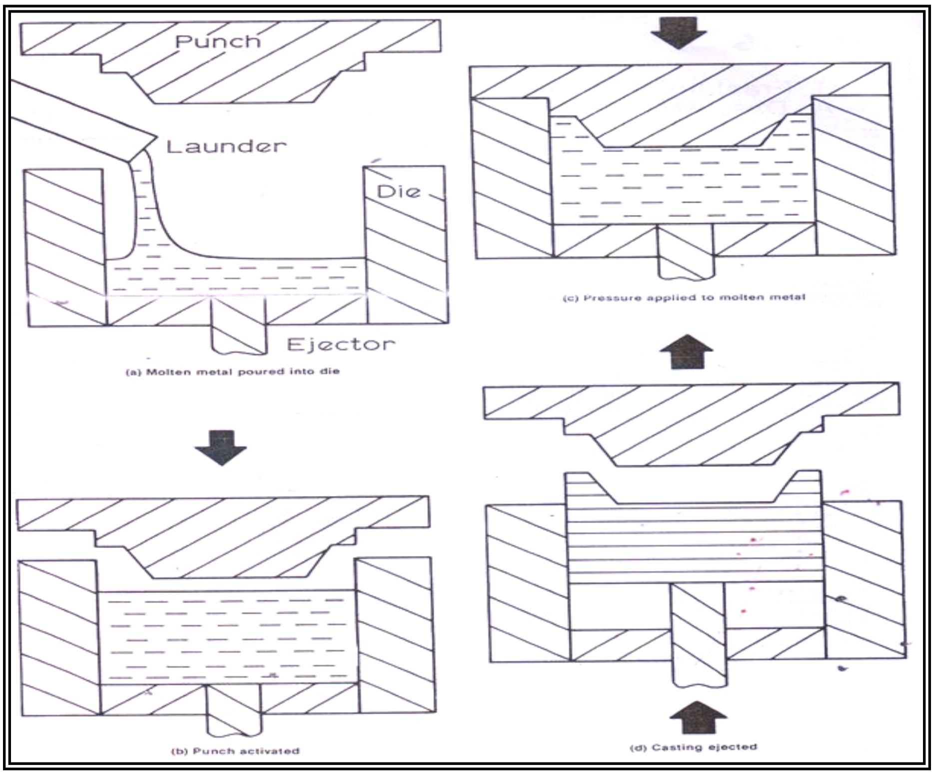

Fig. 2 Direct squeeze die casting process [10].

(a) Molten metal poured into die (b) Punch activated
(c) Pressure applied to molten (d) Casting ejected

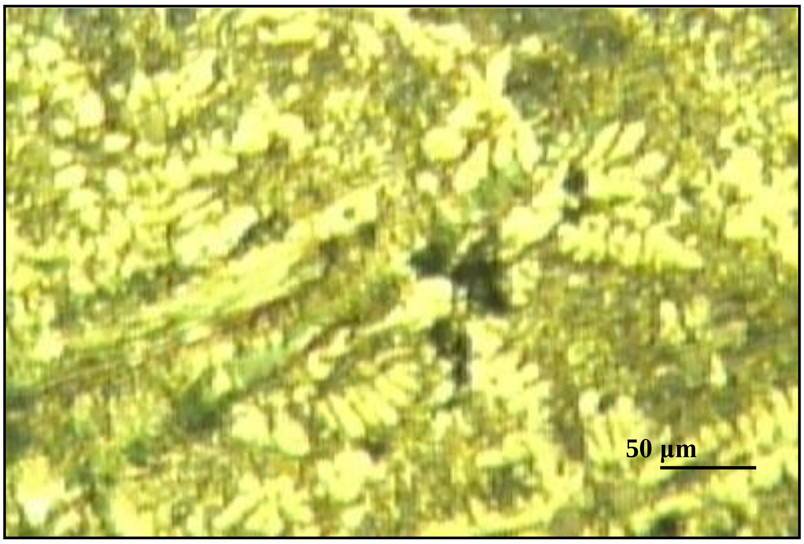

Fig.3 The microsturcture of gravity die cast sample (sample A)

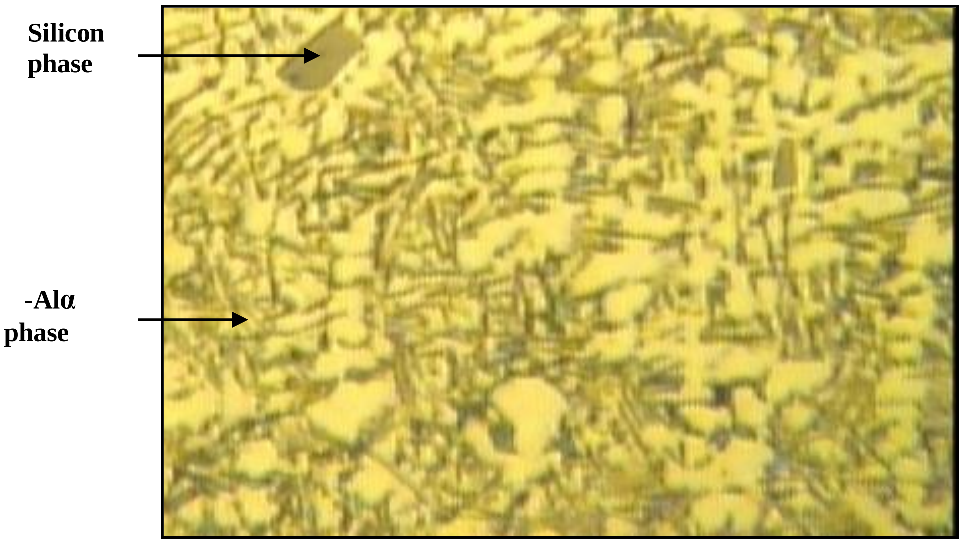

Fig.4 The microsturcture of squeeze cast sample at a applied pressure 7.5MPa (sample A1)

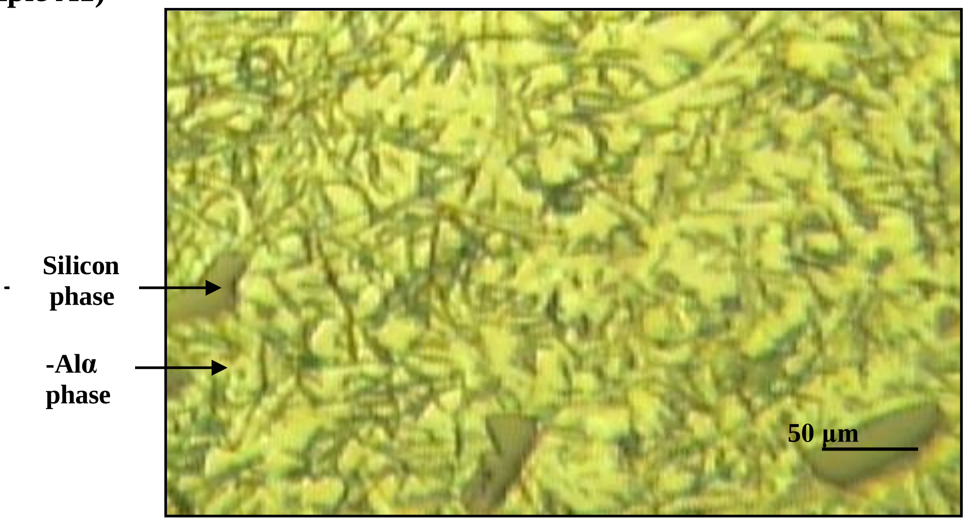

Fig.5 The microsturcture of squeeze cast sample at a applied pressure 23 MPa (sample A2)

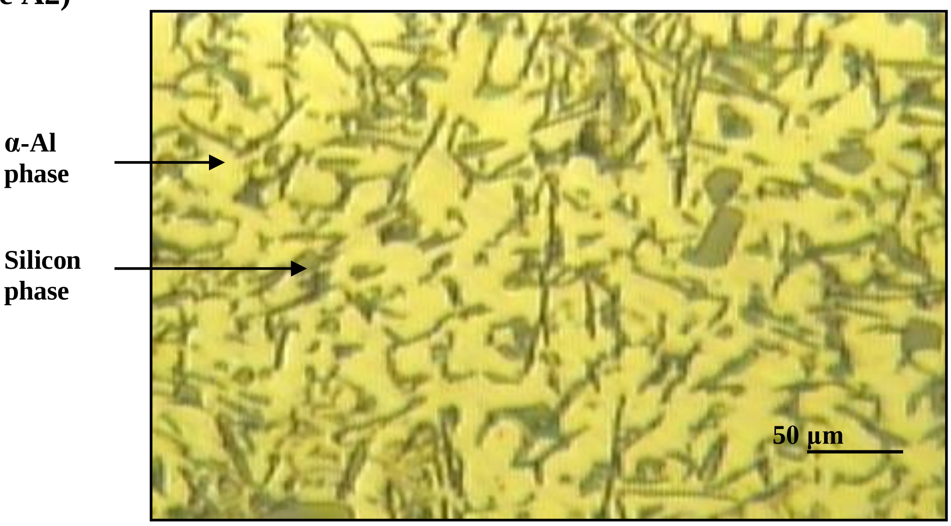

Fig.6 The microsturcture of squeeze cast sample at a applied pressure 38 MPa (sample A3)

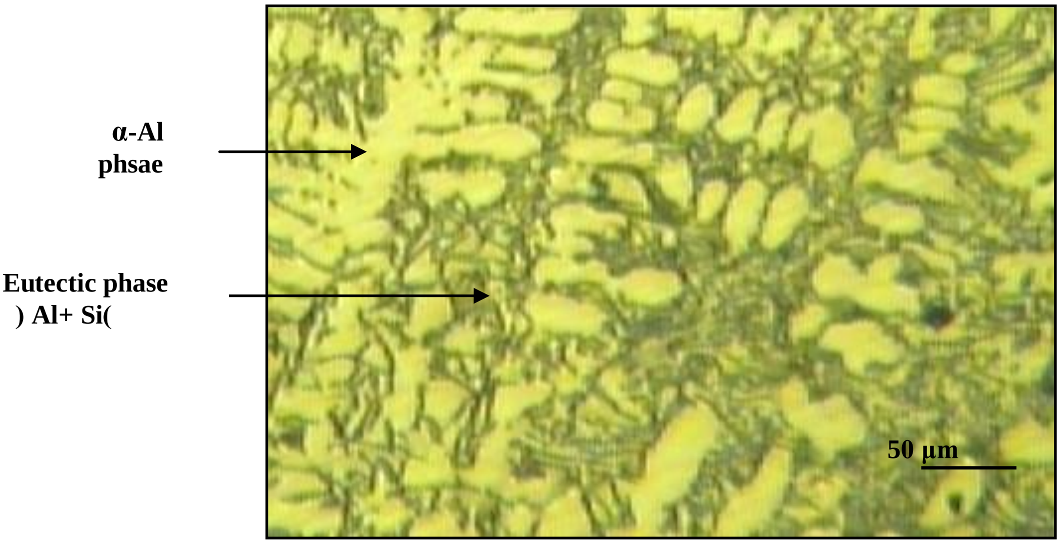

Fig.7 The microsturcture of squeeze cast sample at a applied pressure 53 MPa (sample A4)

SampleA1: Squeeze casting at pressure 7.5 Mpa
SampleA2: Squeeze casting at pressure 23 Mpa
SampleA3: Squeeze casting at pressure 38 Mpa
SampleA4: Squeeze casting at pressure 53 Mpa
Sample A: Gravity die casting

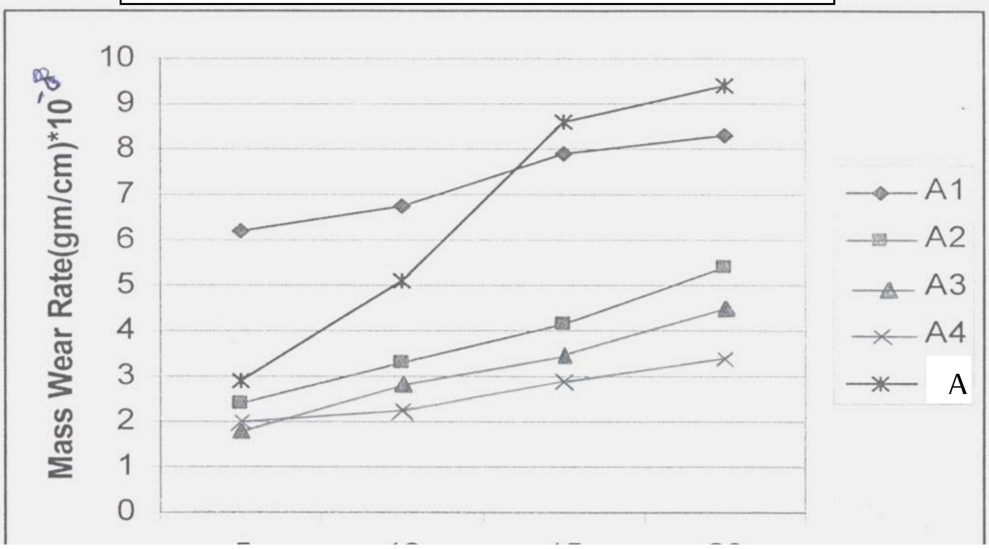

Fig.8 Effect of applied load in wear rate for squeeze cast samples of alloy (Al-12%Si) which are produced at different casting pressures, at a sliding speed of 2.7m/sec and sliding time of 20min during wear test

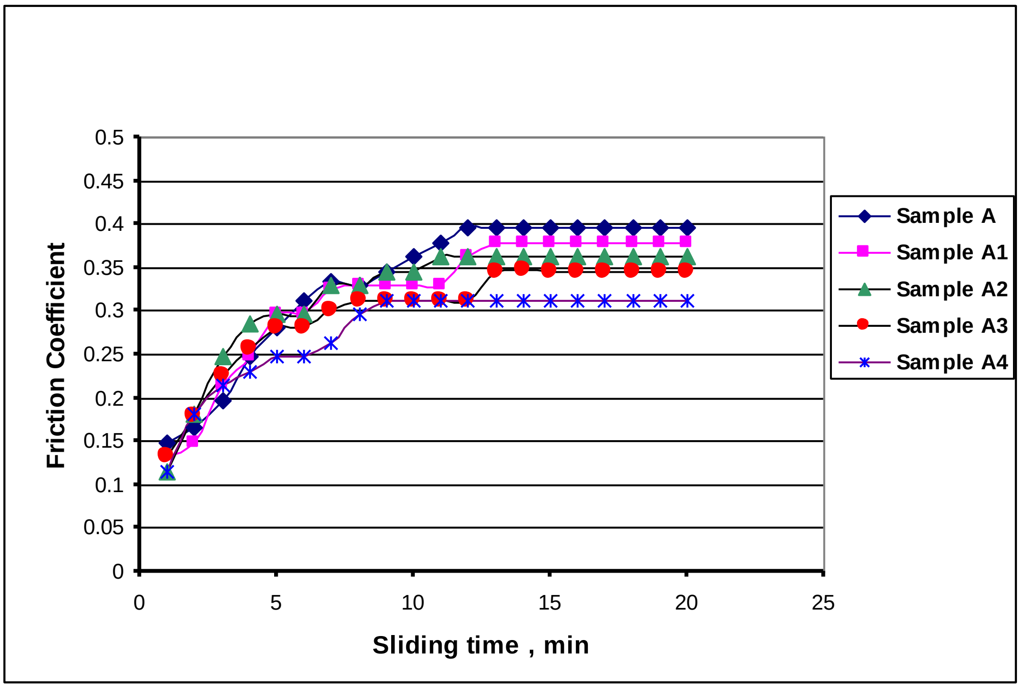

Fig.9 The effect of sliding time in the friction coefficient (μ) for squeeze cast samples of alloy (Al-12%Si) which are produced at different casting pressures, at a sliding speed of 2.7m/sec , applied load of 20N and sliding time of 20min during wear test

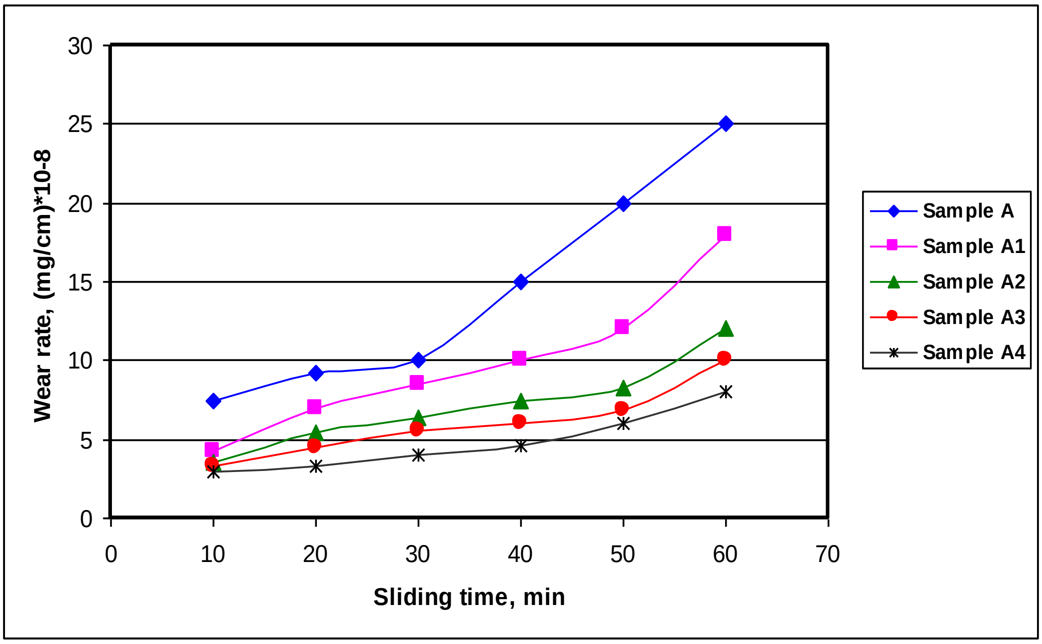

Fig.10 The effect of sliding time in the wear rate for squeeze cast samples of alloy (Al-12%Si) which are produced at different casting pressures, at a sliding speed of 2.7m/sec and applied load of 20N during wear test

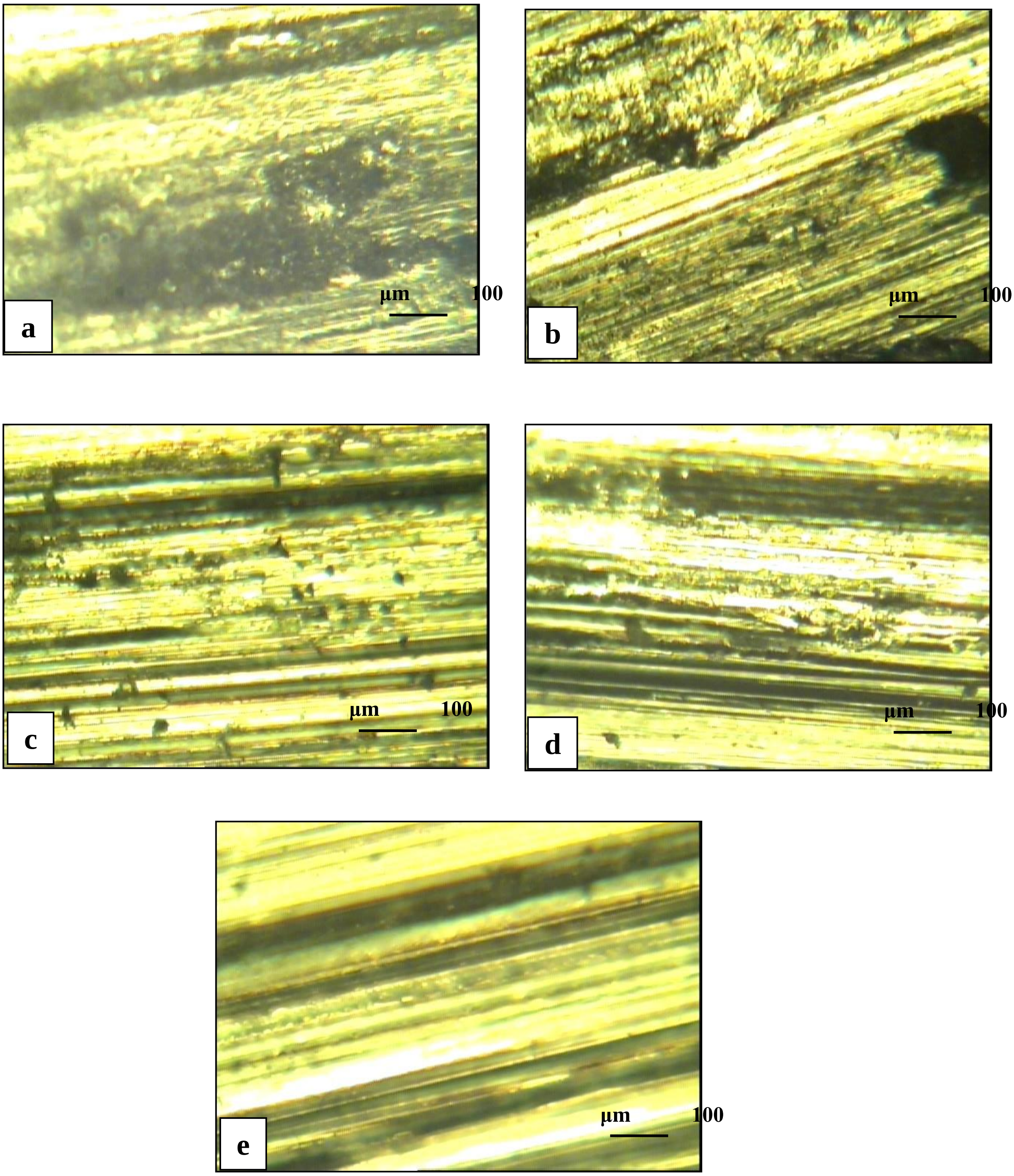

Fig.11 Micrographs of the worn surfaces of the alloy(Al-!2%Si) at a sliding speed of 2.7m/sec , load of 20N and sliding time of 20min

(a) Gravity die cast sample

(b) Squeeze cast sample at applied pressure 7.5 MPa

(c) Squeeze cast sample at applied pressure 23 MPa

(d) Squeeze cast sample at applied pressure 38 MPa

(e) Squeeze cast sample at applied pressure 53 MPa